

Phosphorus limit to the CO₂ fertilization effect in tropical forests as informed from a coupled biogeochemical model

Zhuonan Wang¹, Hanqin Tian¹(tianhan@auburn.edu), Shufen Pan¹, Hao Shi¹, Jia Yang², Naishen Liang³ Latif Kalin¹, Christopher Anderson¹

¹International Center for Climate and Global Change Research, and School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL, USA

²College of Forest Resources, Mississippi State University, Starkville, MS 39762-9681, USA

³Center for Global Environmental Research (CGER), National Institute for Environmental Studies (NIES), Tsukuba, Ibaraki 305-8506, Japan

1. Introduction

Tropical forests store about 72% of global forest biomass carbon (C) and are accountable for about one-third of global net primary productivity (NPP). As essential C reservoirs in the Earth system, tropical forests maintain critical negative feedback to climate warming by slowing the rate of increasing CO₂ concentration in the atmosphere. The CO₂ fertilization effect that increases CO₂ concentrations in leaves enhances plants' capacity in fixing carbon through photosynthesis has been considered as a primary mechanism that maintains and enhances tropical forest productivity. Some TBMs projected a sustained CO₂ fertilization effect on the tropical forests, which has been questioned due to the missed P cycle representation in the models. Meanwhile, the CO₂ fertilization effect on vegetation photosynthesis has been reported to be weakened in recent periods, partially attributable to nutrient limitations. Most TBMs represent tropical rainforests as one plant function type (PFT), i.e., the tropical broadleaf evergreen forests. This PFT has a uniform set of parameters. The parameter of Vcmax25, one of the most important parameters controlling photosynthesis processes is usually prescribed as a constant. However, field data showed that Vcmax25 is highly variable even for the tropical broadleaf evergreen forests.

Building upon our previous study, in this study, we partitioned the tropical rainforests into four tropical rainforest groups assigning with different Vcmax25 and used the improved Dynamic Land Ecosystem Model (DLEM-CNP) to 1) examine the P limitation on CO₂ fertilization effect in tropical forests comparing with C, C-N model; 2) estimate the spatial and temporal patterns of C fluxes in tropical rainforests with integrated C-N-P cycles; 3) explore contributions of the rising CO₂ concentration, climate, land-use change (deforestation), and atmospheric N deposition to the C fluxes of the tropical rainforests during the historical period from 1860 to 2018.

2. DLEM Model

The DLEM model is a highly integrated process-based ecosystem model that couples carbon, nutrients (i.e., nitrogen and phosphorus) and water cycles in terrestrial ecosystems for estimating the hydrological, biogeochemical fluxes and pool sizes at multiple scales from site to region/globe and with time steps ranging from day to year.

Phosphorus cycling

P enters ecosystems in the form of dissolved inorganic P from weathering of minerals, atmospheric deposition and fertilizer. Dissolved inorganic P is the sole source for plants and microbes and can be reversibly adsorbed (secondary mineral P) onto soil particles or lost through leaching. Secondary mineral P can transform into occluded P, which is irreversibly lost to biota. When plants take up P from soils, it enters the plant allocating to growing plant tissues. When plant tissue is shed, part of the phosphorus is resorbed, while the rest enters the litter pools, from where it is either transformed into soil organic matter or mineralized. phosphorus (P) is coupled with C and N dynamics in all the plant biomass and soil pools. The fluxes of P among different biomass pools are driven by C: P ratio.

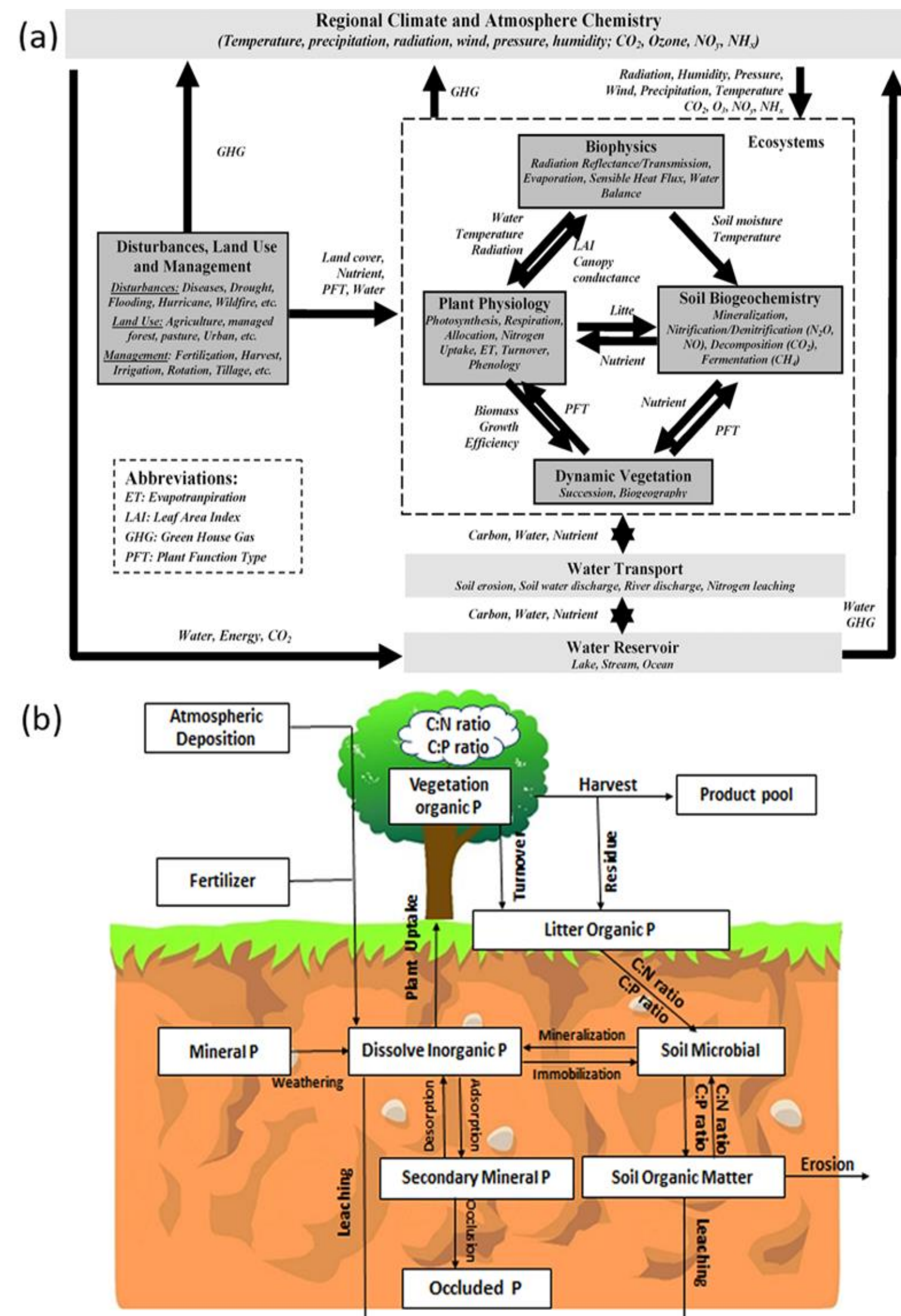


Figure 1 The framework of the Dynamic Land Ecosystem Model. (a) Key components of the DLEM and its linkage to the climate and human systems (Tian et al., 2011) ; (b) Structure of DLEM-CNP P module

$$\frac{dP_{dip}}{dt} = P_w + P_{dep} + P_{fer} + P_{des} + P_{min} - P_{up} - P_{imb} - P_{ads} - P_{ocl} - P_{lch_dip}$$

3. Input data and Model simulation experiments

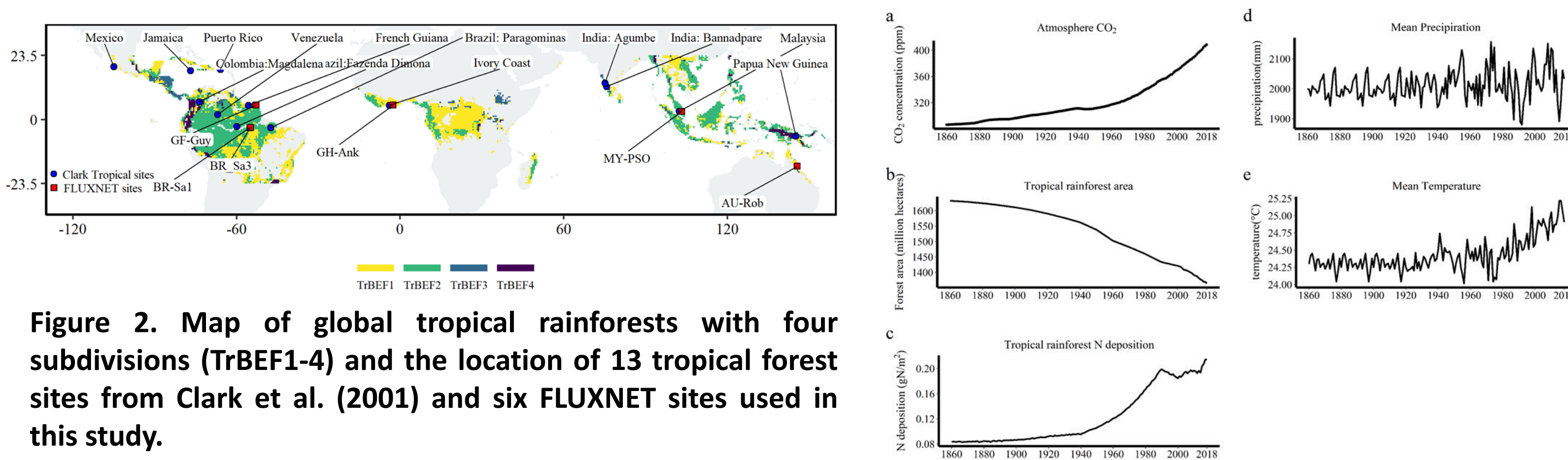


Figure 2. Map of global tropical rainforests with four subdivisions (TrBEF1-4) and the location of 13 tropical forest sites from Clark et al. (2001) and six FLUXNET sites used in this study.

Experiments	CLIM	CO ₂	NDEP	LCU
DLEM-C	1860	1860-2018	1860	1860
DLEM-CN	1860	1860-2018	1860	1860
DLEM-CNP	1860	1860-2018	1860	1860
S0	1860	1860	1860	1860
S1	1860-2018	1860-2018	1860-2018	1860-2018
S2	1860-2018	1860-2018	1860-2018	1860
S3	1860-2018	1860	1860-2018	1860-2018
S4	1860-2018	1860-2018	1860	1860-2018
S5	1860	1860-2018	1860-2018	1860-2018

Table 1 Experimental Design of DLEM-CNP Simulations from 1860-2018.

Figure 3. The input data of the DLEM-CNP. (a) Atmospheric CO₂ concentration; (b) Intact tropical forest areas; (c) Average N deposition across tropical forest areas; (d) Annual precipitation across tropical forest areas; (e) Average temperature across tropical forest areas.

First, the DLEM-C (without N, P limitation, which was executed with the same model code but no N, P limitation on photosynthesis or decomposition), DLEM-CN (without P limitation, assuming P saturation), DLEM-CNP (with N, P limitation) were driven by contemporary CO₂ from 1860-2018 to examine the effects of nutrients limitation on the CO₂ fertilization effect. Then, we designed six numerical experiments (S0 to S5) to simulate the impacts of individual environmental factors on C fluxes (Table 1).

4. Model validation

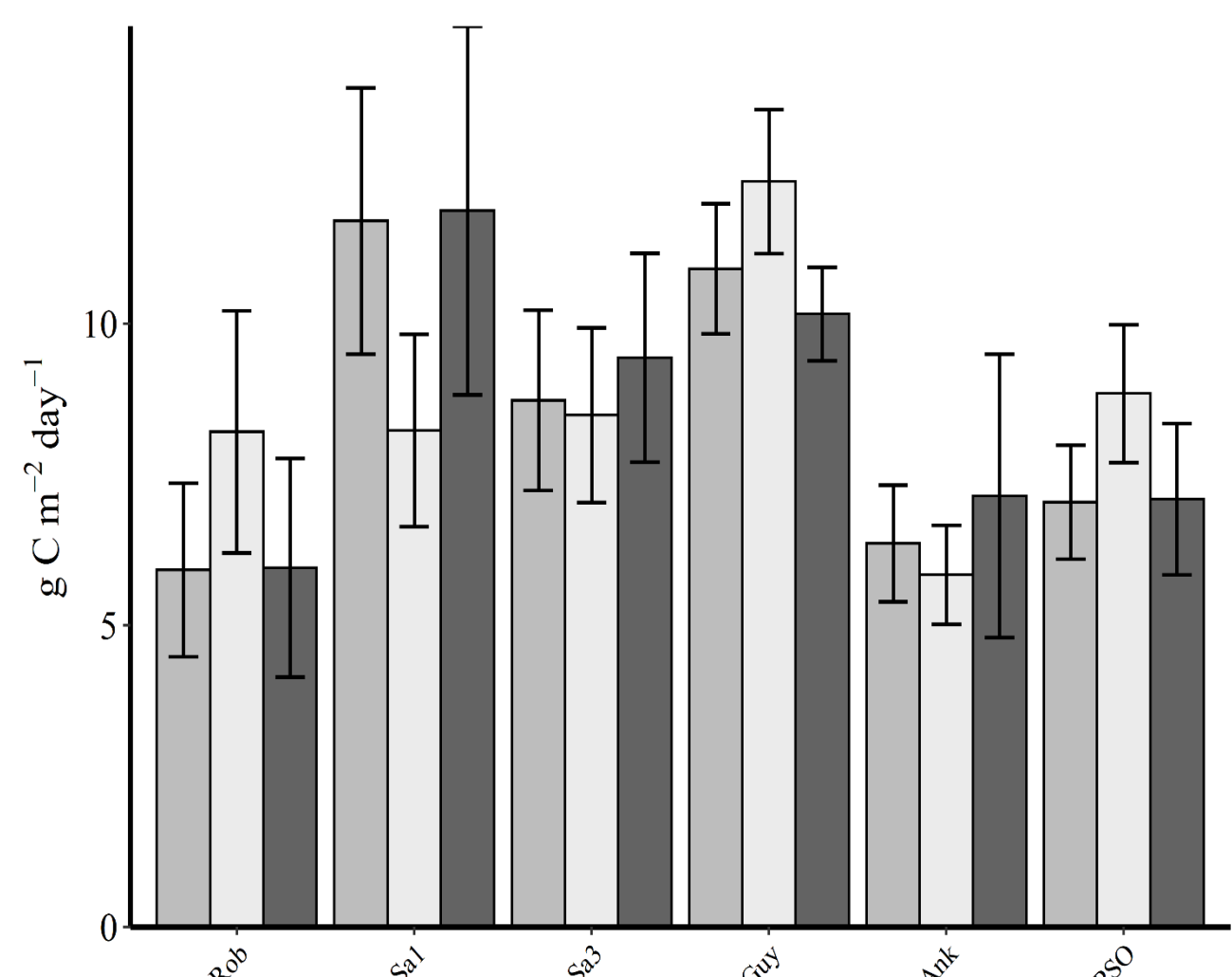


Figure 4. Comparison of the daily average GPP between observations at FLUXNET sites and model simulations. Model simulations are derived using the average Vcmax25, and varied Vcmax25 in the four subdivided TrBEFs zones, respectively.

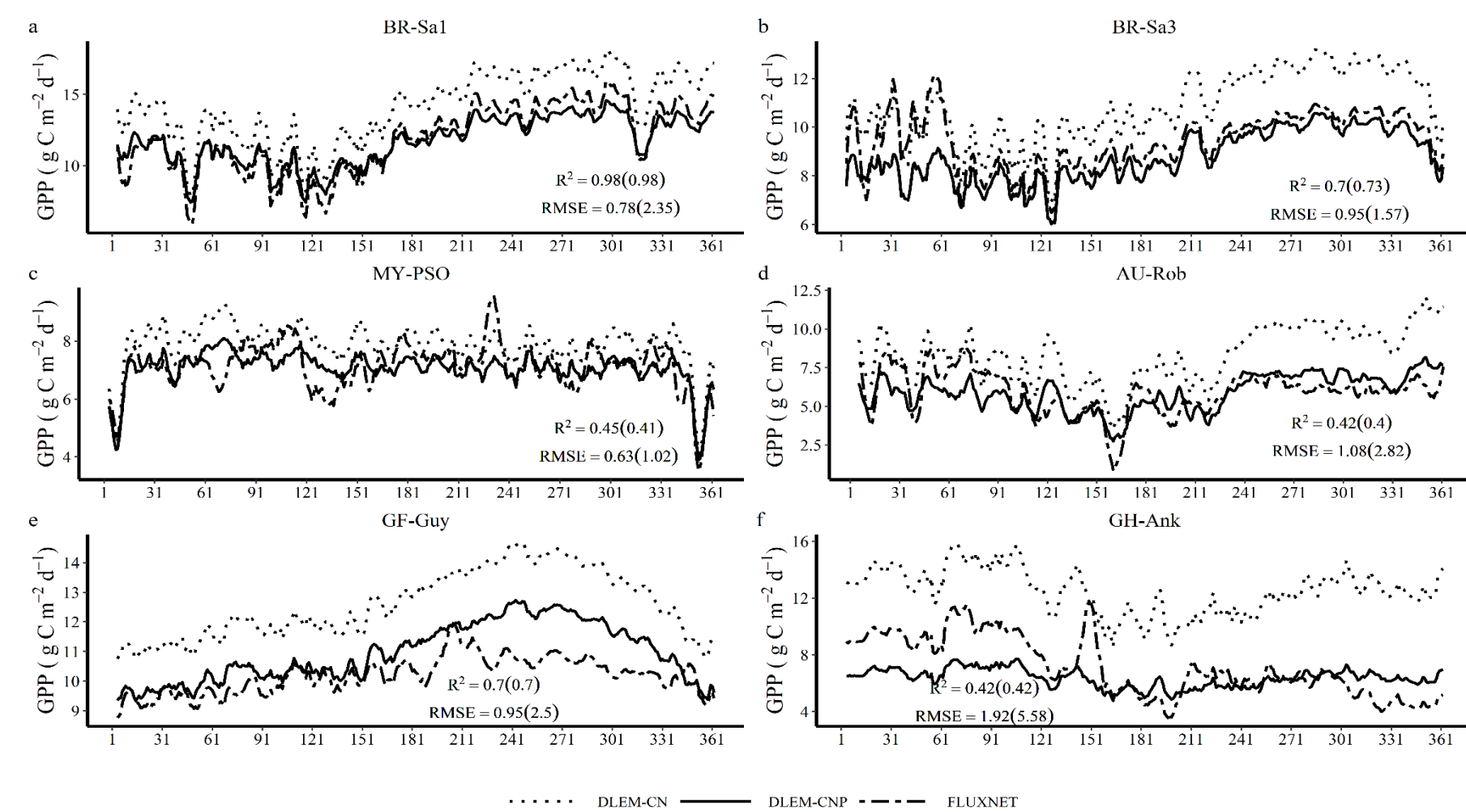


Figure 5. Comparison of the daily gross primary productivity (GPP) between observations and model simulations at the selected FLUXNET sites. RMSE is the root-mean-squared error. The DLEM-CN model corresponds to performances given within parenthesis.

5. Results

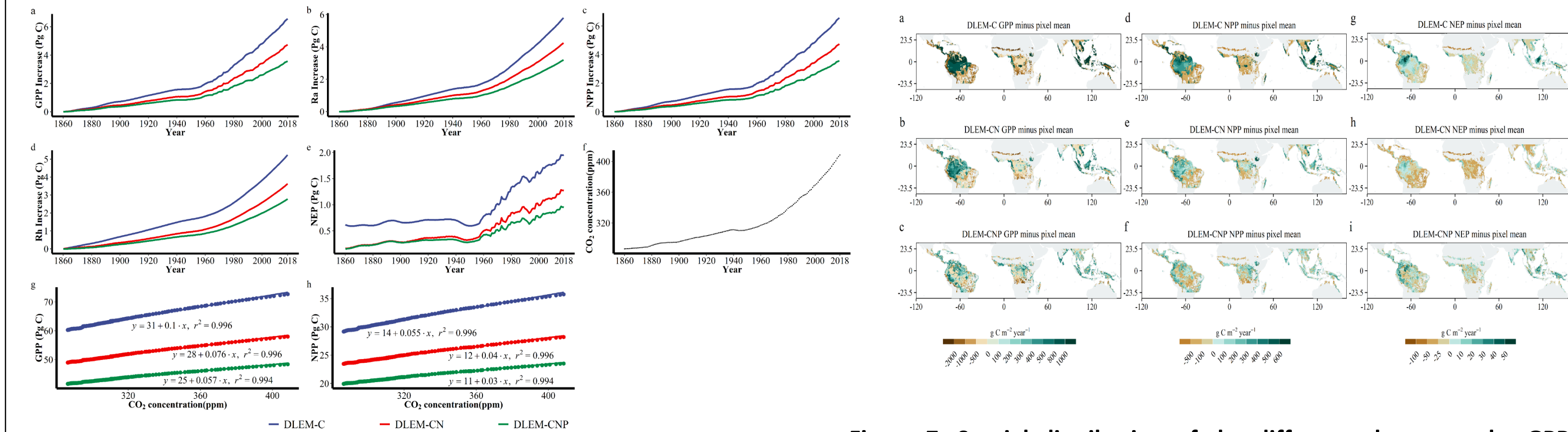


Figure 6. The increased GPP (a), Ra (b), NPP (c), Rh (d), and annual NEP (e) in the tropical rainforest from 1860-2018 under historical atmospheric CO₂ concentration, simulated by DLEM-C (blue), DLEM-CN (red), and DLEM-CNP (green), respectively; figure (a,b,c,d) are with reference to 1860. Figure (f) is the CO₂ concentration from 1860-2018. Figures (g) and (h) are correlations between GPP, NPP, and annual CO₂ concentration, respectively.

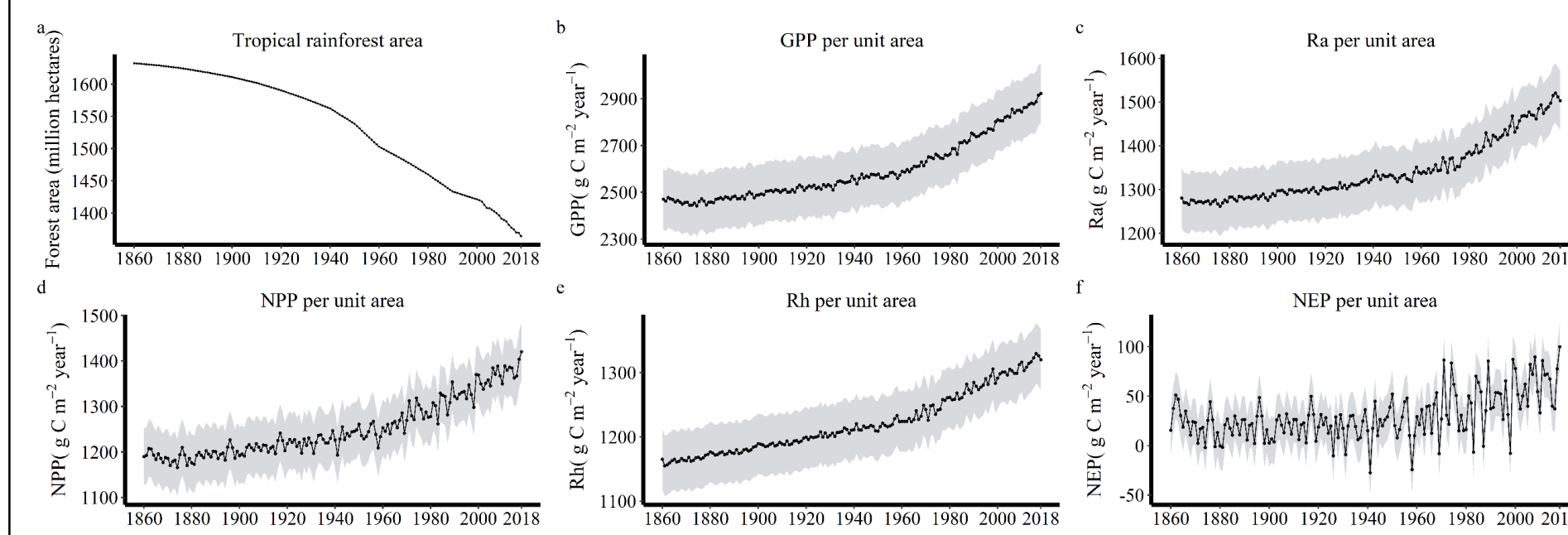


Figure 7. Spatial distribution of the difference between the GPP, NPP, and NEP annual mean and the grids mean simulated by the DLEM-C, DLEM-CN, DLEM-CNP in the 2010s. Difference between the GPP annual mean and the grids mean simulated by (a) DLEM-C; (b) DLEM-CN; (c) DLEM-CNP in the 2010s. Difference between the NPP annual mean and the grids mean simulated by (d) DLEM-C; (e) DLEM-CN; (f) DLEM-CNP in the 2010s. Difference between the NEP annual mean and the grids mean simulated by (g) DLEM-C; (h) DLEM-CN; (i) DLEM-CNP in the 2010s.

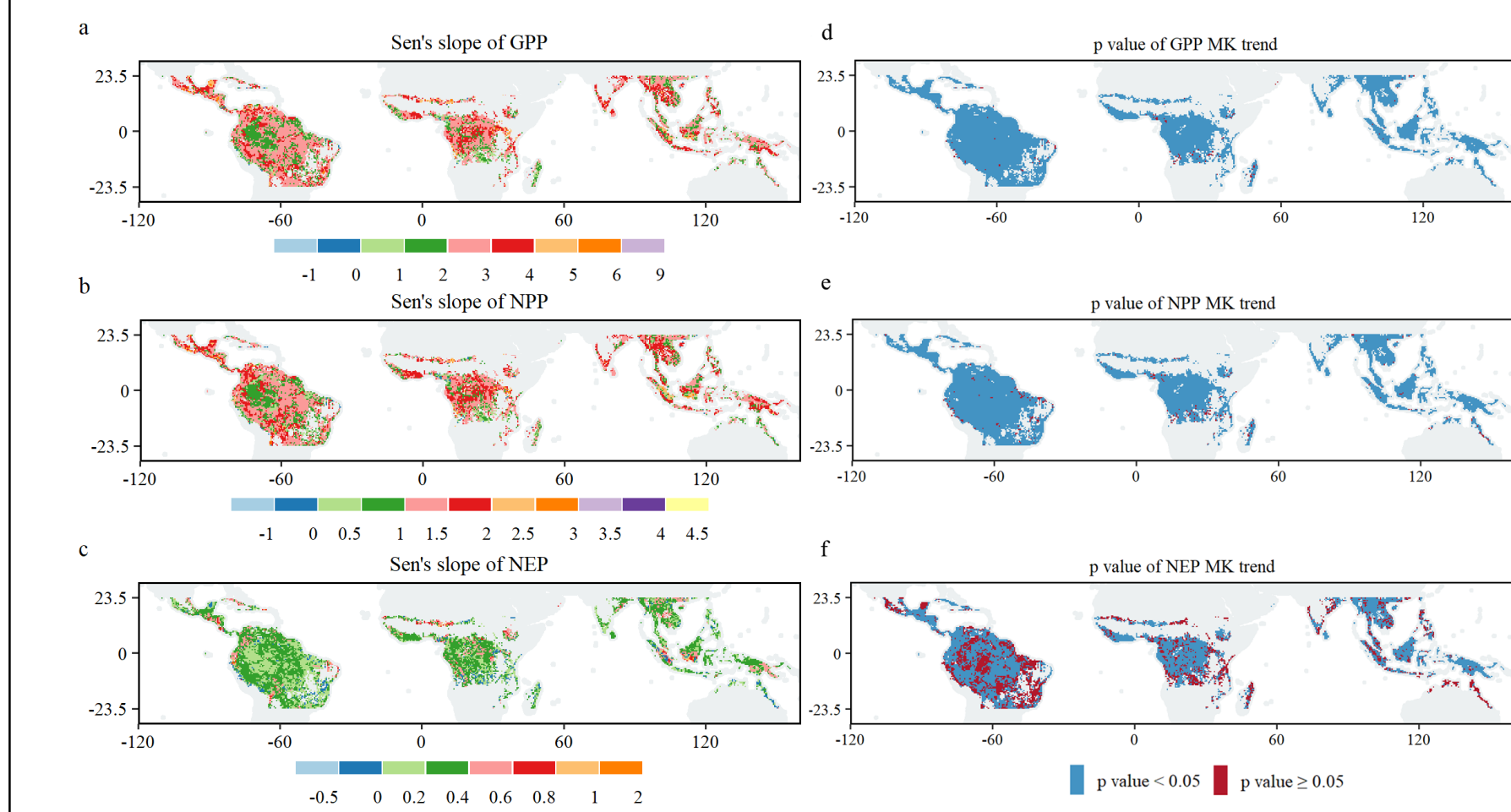


Figure 8. Inter-annual variations of tropical forest GPP (a), NPP (b), and NEP (c; Pg C per year) for 1860-2018 simulated by the DLEM-CNP driven by all historical environmental factors. The shade means one standard deviation (sd) of each simulation.

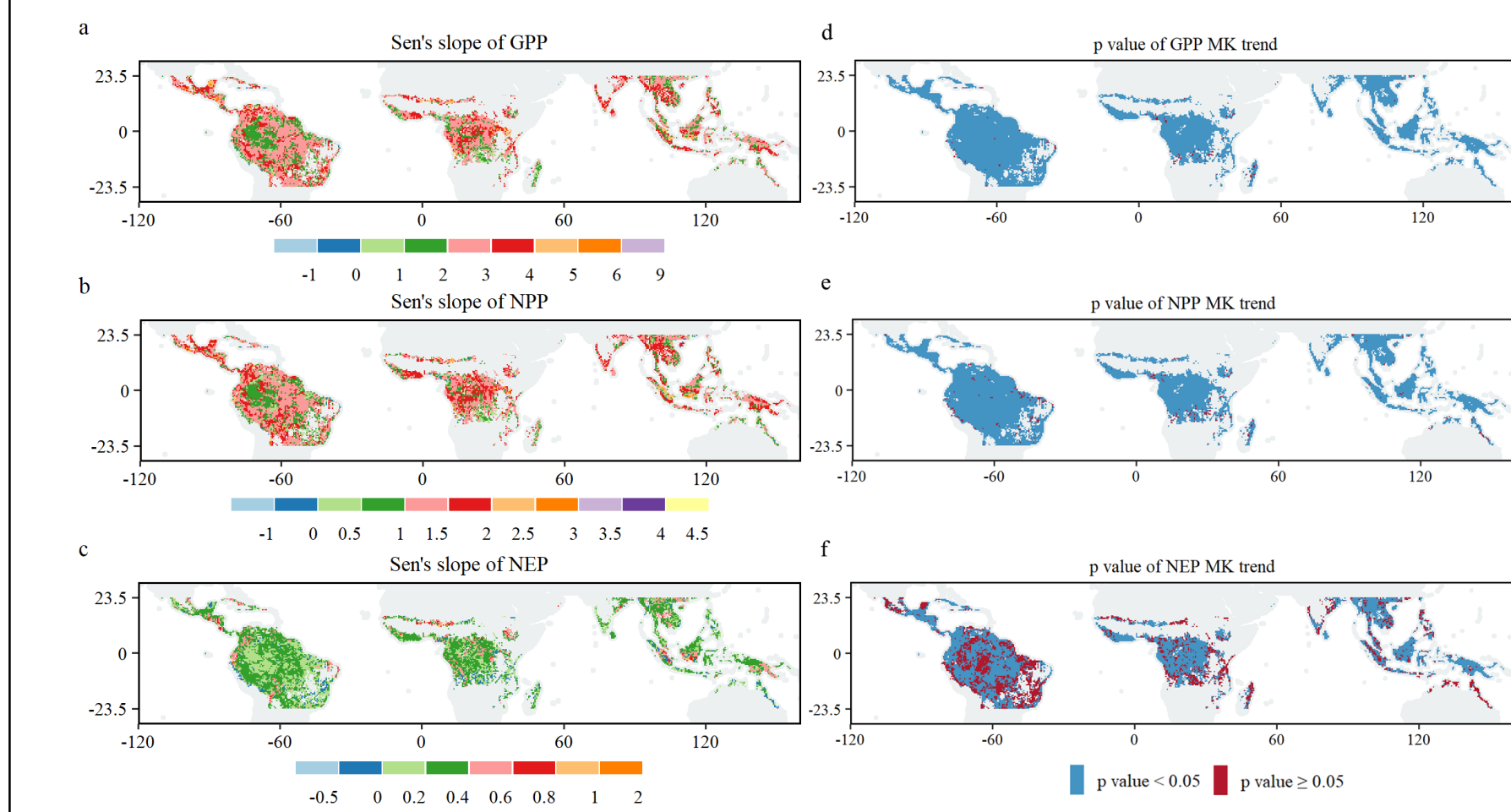


Figure 9. Sen's slope of the tropical rainforests annual GPP (g C m⁻² year⁻¹, a), NPP (g C m⁻² year⁻¹, b), and NEP (g C m⁻² year⁻¹, c) during 1860-2018. And area of the tropical forests with significant and insignificant trends in annual GPP (d), NPP (e), and NEP (f). The significance of the trend is estimated through the MK trend test, and p-values less than 0.05 are significant.

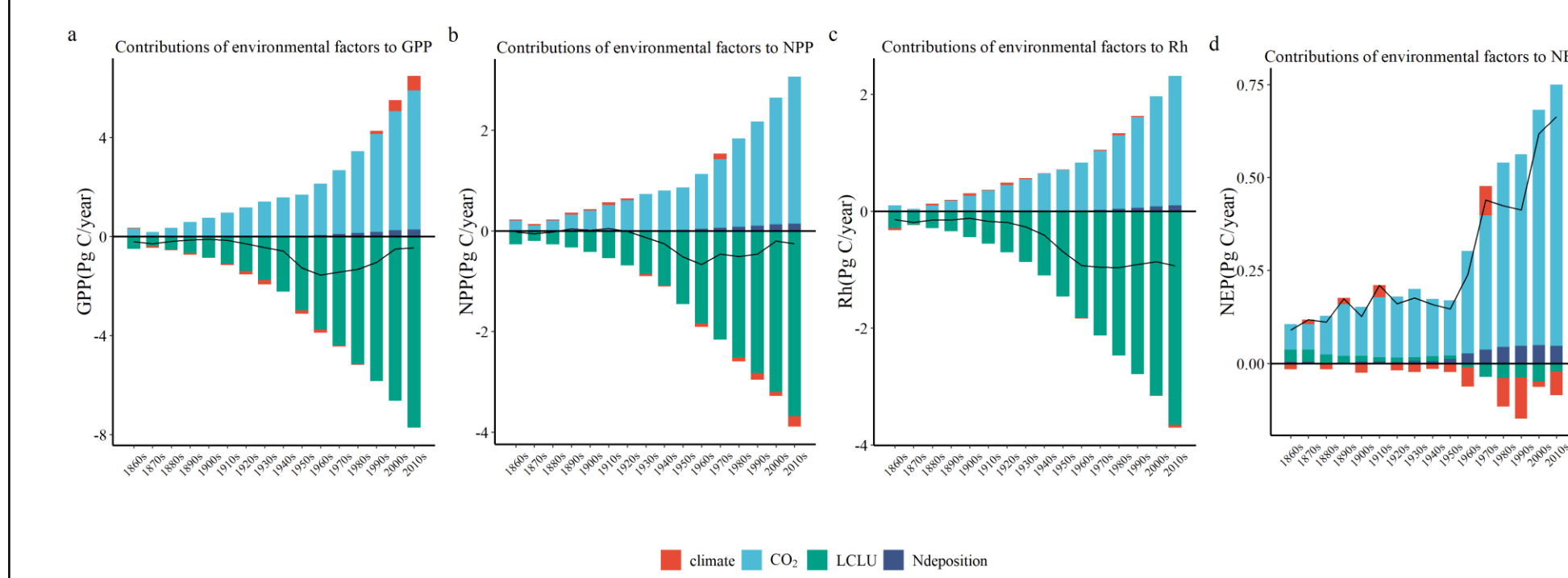


Figure 10. Changes in tropical rainforests decadal GPP (a), NPP (b) Rh (c), and NEP (d) contributed by multiple environmental factors, including climate variability (climate), atmospheric CO₂ (CO₂), atmospheric N deposition (N deposition), and land-cover land-use change (LCU) during 1860-2018 simulated by the DLEM-CNP. Contributions of environmental factors were estimated by the difference between simulation scenarios (Table 1). Black lines represent the combined effects of all the driving factors(S1-S0).

Our model results showed that consideration of the P cycle reduced the CO₂ fertilization effect on tropical rainforests gross primary production (GPP) by 25% and 45%, NPP by 25% and 46%, and net ecosystem production (NEP) by 28% and 41% to the CO₂ fertilization effect relative to CN-only and C-only models. The DLEM-CNP estimated that the tropical rainforest GPP increased by 17 %, Ra increased by 18%, NPP increased by 16 %, Rh increased by 13%, and NEP increased by 121%, from the 1860s to the 2010s, respectively. Additionally, factorial experiments with DLEM-CNP showed that the enhanced GPP and NPP benefiting from the CO₂ fertilization effect had been offset by the deforestation impacts on GPP and NPP reduction. Our study highlights the importance of P limitation on the C cycle and the weakened CO₂ fertilization effect due to P limitation in tropical forests.

Acknowledgment

This study has been partially supported by the US National Science Foundation (1210360, 1243232);), the CSC Scholarship.